Mars

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Introduction

Missions to Mars and beyond are lengthy and expensive, and dangerous. The Red planet has fascinated mankind for thousands of years. Many thousands of years of position data have been recorded. We have robotic spacecraft in Martian orbit, and landers and rovers on the surface. The next step is to go there, with boots on the ground. Decades of time, and hundreds of millions of dollars are required. Columbus would have approved. We just need to get off our...planet, and get going.

Author

The author has a BSEE in Electrical Engineering from Carnegie-Mellon University, and Masters Degrees in Applied Physics and Computer Science from the Johns Hopkins University. During a career as a NASA support contractor from 1971 to 2013, he worked at all of the NASA Centers. He served as a mentor for the NASA/GSFC Summer Robotics Engineering Boot Camp at GSFC for 2 years. He teaches Embedded Systems for the Johns Hopkins University, Engineering for Professionals Program, and has done several summer Cubesat Programs at the undergraduate and graduate level. Now he supports International collaborative open-source projects, and STEM Programs.

A note on Units

I am fairly conversant in both English and Metric units (what is the metric equivalent of furlongs per fortnight?). Metric (SI) is mandated for NASA usage now, for interchangeability with our partner space faring nations. When a lot of the legacy flights discussed here were flown, English units were the norm. I have tried to keep the units comparable to the mission at the time. Conversions are easy enough, but units conversion is a source of error. It has caused loss of missions and lives. It's not what you know about units and measurement, its how you think. And, I still

think English units (even the English use Metric now), and convert in my head or on my phone.

For scientific/engineering work, the Metric system is well thought out. For artisans, the English system served well, as most units were divisible by 2. Which is easy. Fold the cloth. Hopefully, when we are all taught Metric first, some one will still remember the conversions. You just need a good slide rule....

Mars, the planet

Mars is the next planet out from the Sun, from the Earth. It is almost the smallest, but Mercury has that title. The red of the red planet comes from iron oxides. Predominately, the iron ore hematite is present. Having a slight gravity, it has a thin atmosphere. This means that many things evaporate into space, such as water. If water exists on Mars, it is in the form of ice. Indeed, the Martian poles have water ice. There was a large volume of underground ice discovered in the area of Utopia Planitia. Mars can be seen by the naked eye, from Earth's surface. Mars scores the largest the largest known volcano in the solar system, Olympus Mons. It has two moons. It's spin axes is tilted like the Earth's, so it has seasons. It consists mostly of desert terrain, with tall mountains and impact craters.

The one-way light time between Earth and Mars varies between 3 and 29 minutes, depending on the relative positions in their orbits. This affects the communication between the Earth, and the various orbiters, landers, and rovers. In some cases, when Mars and the Earth are on opposite sides of the Sun, communication is not possible. Optical telescopes on Earth can resolve features down to a size of 300km, due to the distortions of Earth's atmosphere. This drives the many imaging missions that have visited the red planet.

Mars' size is about half of Earth's, but it has about the same dry-land surface area. It has a metallic core, but not a significant magnetic field. We have good data on the composition of the surface courtesy of the Phoenix lander. Surface features from a

variety of sources seem to show erosion. More water certainly existed on Mars in earlier periods. The poles are very cold, and covered in solid carbon dioxide. The United States Geologic Survey maintains accurate maps of the surface. Mars has a large number of impact craters, due to the thin atmosphere.

The Mars surface is blasted by the solar wind, due to its thin atmosphere, and lack of a magnetic field. Most of the Martian atmosphere is carbon dioxide. Methane is present, suggesting a biological origin, but other sources are also possible. The current Indian Mars mission is specifically searching for methane in the atmosphere. In June 2018, NASA disclosed in a press conference that the Curiosity rover had observed seasonal fluctuations of atmospheric methane levels. These fluctuations peaked at the end of the Martian summer at 0.6 parts per billion. Methane is of interest, as it could be used as rocket fuel, for return missions.

Mars has awesome dust storms, some that cover the entire planet. Due to its distance from the Sun, Mars only receives about 45% of the solar energy that the Earth gets. It can warm up on the surface during the day, but it always plummets at night, usually to where the carbon dioxide in the atmosphere freezes. Wind speeds can get up to 60 mph or so, but the atmosphere is so thin, you many not notice. The dust storms generate large electrostatic fields.

Mars was one of the items of interest for early astronomers. The Greeks and Romans named it after their god of war. The Sumerians called it Nergal, after their god of war. In Niveveh, the cult of the red planet called it “the star of judgment of the fate of the dead.” The Egyptians were well aware of the planet, and the strange path it took across the heavens. Aristotle noted that Mars disappeared behind the moon, proving it was further away. Galileo was the first to study Mars with a telescope. The Chinese called it the fire star.

If you look in the Mayan document called the Dresden Codex, you will see an extensive list of observations of Mars, what we now call an Ephemeris.

Asteroids, chunks of rock from Mars, are usually found in Antarctica. My old college college professor figured out why, and wrote the definitive paper. I haven't a clue.

One thing that would make Mars more habitable for humans has been very bad for Venus, and is a problem for Earth. Greenhouse gases on Mars would add density to the atmosphere, and control the wide swings of temperature.

Schiaparelli and the Canals

The story of Mars is not complete without a discussion of Schiaparelli's discovery of the Martian canals. He was an Italian astronomer, from the University of Turin, who spent 40 years at an observatory in Milan. In 1877, he observed and reported a network of linear structures on the planet, and termed them “canali”, the Italian word for channels. He wrote an 1893 book, “Life on Mars.” A strong supporter of life on Mars was Percival Lowell, at the observatory in Flagstaff, Arizona. The later Italian astronomer Cerulli decided the channels were optical illusions, This seems to have been born out, due to the many close up observations of the planet by spacecraft. Schiaparelli went on to work on binary stars, and the linkage between comets and meteor showers. He did extensive work on the observation of Mars and Venus.

Mars' moons

Mars has two moons, Phobos and Deimos. These were discovered in 1877 at the U. S. Naval Observatory in Washington, D. C. by Asaph Hall. He was using the observatory's 26 inch refracting telescope. The names come from the son's of the Greek god of War, Ares. Two moons of Mars are mentioned by Jonathan Swift in Gulliver's Travels, and there was wide speculation of their existence. Many of the surface features on the moons are named after characters in Swift's Sci-Fi novel.

Phobos orbits Mars with a semi-major axis of 9375 km and an orbital period of 7.65 hours. Deimos has a semi-major axis of 23,450 km and orbital period of 30.35 hours. Viewed from Mars' surface, Phobos appears about 1/3 the size of our full moon. Due to distance and geometry, there are total lunar eclipses of Phobos almost every night. The small size of the moons means there are no total solar eclipses on Mars. Both moons are in tidal lock with Mars, so only one side can be seen from the surface. There is an interesting feature called the Phobos monolith. It is a rock about 85 meters across.

Phobos rises in the west and sets in the east, while Deimos does the opposite. Deimos's altitude is above synchronous, and takes it 2.7 days to fall below the horizon. The orbital period for Phobos is 7.6 hours, and 30.3 hours for Deimos.

One theory is that the moons are captured asteroids, another is that they resulted from a collision. Both have been extensively photographed, but no samples have been taken as of this writing.

Mars has a series of Trojans, which are objects that share it's orbit around the Sun. They are clustered around the leading (L4) and trailing (L5) Lagrange points, at 60 degrees ahead and behind the Planet. There are seven known Trojans. Again, they may be captured asteroids, or results of collisions. Since the Lagrange points are gravity nulls, stuff tends to accumulate there.

Von Braun's and Ley's vision

Wernher von Braun produced a detailed technical project plan for getting to Mars in 1952, but he had been thinking about it long before that. He and fellow rocket enthusiast Willy Ley worked on Mars Mission Concepts, a long time before the first person rode a rocket.

Mars Missions

As of this writing, three Nations have sent missions to Mars: The United States, Russia, and India. The ESA, consisting of a number of European nation's, has also implemented Mars missions.

United States Missions to Mars

The United States has been involved in Mars exploration with missions starting in 1964, and continuing, as of this writing. That';s more than 50 years of exploration, at a great distance.

The Mariner-3 mission to Mars in November of 1964 suffered a mission failure when the payload fairing failed to release. Mariner-4, launched 2 weeks later, was a success, as was Mariner-6 in 1969. (Mariner-5 went to Venus). Mariner 7 did a successful fly-by in 1969, but Mariner 8 had a launch failure.

Mariner-9 was launched in 1971, and entered Martian orbit. It was a successful mission, and was deactivated 516 days later.

Viking

The Viking program was a pair of spacecraft sent to Mars in 1975. Each spacecraft consisted of an orbiter, and a lander. The Viking landers used a Guidance, Control and Sequencing Computer (GCSC) consisting of two Honeywell 24-bit computers with 18K of memory, while the Viking orbiters used a Command Computer Subsystem (CCS) with two custom-designed 18-bit bit-serial processors. They were programmed in assembly language. The Honeywell machine had 47 instructions, and used two's complement representation for data.

After entering Mars orbit, the spacecraft extensively imaged the surface for a month. A target landing site was selected, and the landers went on their ways. The orbiters served as communication relays for the landers. They deployed solar panels for power, rated at 620 watts, at Mars' distance from the Sun.

The Landers were stationary platforms, not rovers. They used parachutes and retro-rockets to safely reach the surface of the planet. For power, the lander platforms had radioisotope thermoelectric generators, providing 30 watts continuously. There were a variety of instruments including cameras, wind direction and velocity sensors, and a mass spectrometer. The instruments that targeted the detection of life activities did not see significant results. The Viking 2 orbiter operated until July 1978, and its lander operated until April of 1980. The Viking 1 orbiter lasted until August of 1980, and the lander until November of 1982. Viking kicked off the search for organic molecules on Mars in 1976.

The landers are still on the surface, and could be moved to the Martian Museum of Exploration (when that is built).

The Mars Observer spacecraft suffered a launch failure in 1992. It was also termed the Geoscience/Climatology Orbiter. Three days prior to Mars orbit insertion, communication with the spacecraft was lost.

Mars Global Surveyor, launched in 1996, operated successfully for 7 years. It imaged the surface to uncover landing sites, and served as a communications relay back to Earth for surface assets. It also served as a Martian weather satellite, interested in large dust storms that form on the surface. It had completed its primary mission in January of 2001, but continued to operate until November of 2006.

Surveyor was kept in a sun-synchronous orbit, where it passes over a given point on the surface at the same time (and Sun angle) each day. Surveyor was responsible for confirming the existence of water ice on Mars. It also photographed the Mars Exploration Rover *Spirit* and its wheel tracks on the surface.

Mars Pathfinder

The Mars Pathfinder mission landed on Mars on July 4, 1997. It carried a Rover named Sojourner, which was a 6-wheeled design, with a solar panel for power, but the batteries were not rechargeable. The rest of the lander served as a base station. Communication with the rover was lost in September. The Rover used a single 8-bit CPU with 64k of ram. It communicated with Earth via the base station using a 9600 baud UHF radio modem. The communication loss leading to end of mission was in the base station communication, while the Rover remained functional. The Rover had three cameras, and an x-ray spectrometer.

The computer in the mission base station on Mars was a single RS-6000 32-bit CPU. The software was the VxWorks operating system, with application code written in the c language. The base station computer experienced a series of resets on the Martian surface, which lead to an interesting remote debugging scenario.

The operating system implemented pre-emptive priority thread (of execution) scheduling. The watchdog timer caught the failure of a task to run to completion, and caused the reset. This was a sequence of tasks not exercised during testing. The problem was debugged from Earth, and a correction uploaded.

The failure turned out to be a case of priority inversion. The higher priority task was blocked by a much lower priority task that was holding a shared resource. The lower priority task had acquired this resource and then been preempted by several medium priority tasks. When the higher priority task was activated, it detected that the lower priority task had not completed its execution.

The reset had the effect of wiping out most of the data that could show what was going on. This behavior was not seen during testing. It was successfully debugged and corrected remotely by the JPL team. Interplanetary cntrl-alt-delete.

Mars Climate Orbiter

The spacecraft was lost on Mars in September 1999. The requirements did not specify units, so JPL used SI (metric) units and the contractor Lockheed Martin used English units. This was not caught in the review process, and led to the loss of the $125 million mission. The spacecraft crashed due to a navigation error. The computer architecture was a single 32-bit RAD6000 cpu, with 128 megabytes of ram, and 18 megabytes of flash memory.

VxWorks, from Wind River systems, was the operating system with flight software developed at Lockheed Martin Corporation. Sensors and Actuators included dual 3-axis gyros, a star tracker, dual sun sensors, eight thrusters, and four reaction wheels.

The primary cause was human error. Specifically, the flight system software on the Mars Climate Orbiter was written to calculate thruster performance using the metric unit Newtons (N), while the ground crew was entering course correction and thruster data using the Imperial measure Pound-force (lbf). This error has since been known as the *metric mix-up* and has been carefully avoided in all missions since by NASA.

"The root cause of the loss of the spacecraft was the failed translation of English units into metric units in a segment of ground-based, navigation-related mission software, as NASA has previously announced," said Arthur Stephenson, chairman of the Mars Climate Orbiter Mission Failure Investigation Board. "The failure review board has identified other significant factors that allowed this error to be born, and then let it linger and propagate to the point where it resulted in a major error in our understanding of the spacecraft's path as it approached Mars.”

Mars Polar Lander

The Mars Polar lander didn't, in 1999. It took with it the Deep Space 2 probe. The hard landing may have been due to a premature engine cut-off.

Mars Odyssey

The Odyssey, launched in 2001 remains operational as of this writing, and is expected to remain so through 2025. It was deployed to search for surface ice, and serve as a communications relay. It has been for some time the main communication link between landers and rovers on the surface, and Earth. It is also tasked with characterizing the surface radiation environment for future crewed surface missions.

It is in Sun-synchronous orbit around Mars. It helped to determine a landing site for the Mars Science Laboratory.

MER – Mars Exploration Rovers *Spirit & Opportunity*

The MER are six-wheeled, 400 pound solar-powered robots, launched in 2003 as part of NASA's ongoing Mars Exploration Program. *Opportunity* (MER-B) landed successfully at Meridiani Planum on Mars on January 25, 2004, three weeks after its twin *Spirit* (MER-A) had landed on the other side of the planet. Both used parachutes, a retro-rocket, and a large airbag to land successfully, after transitioning the thin atmosphere of Mars.

For power, they use 140 watt solar arrays and Li-ion batteries. The Rovers require 100 watts for driving, One problem that was noted was that the Martian dust storms cover the solar panels with fine dust, reducing their efficiency. This resulted in the use of a radioisotope generator on a subsequent mission. It's been observed that Rovers often use more energy in path planning, than to execute the actual path.

The onboard computer uses a 20 MHz RAD6000 32-bit CPU with 128 MB of RAM. There is a 3-axis inertial measurement unit, and nine cameras The Rovers communicate with Earth via a relay satellite in Mars orbit, Odyssey or Mars Global Surveyor. They also have the ability to communicate directly, at a lower data rate.

The lander and rover include Xilinx FPGA's for mission critical

functions. The rover's motor controllers are implemented in the FPGA's. These operated through the worst Solar Flare ever measured. These are particularly bad at Mars, since it has no discernible magnetic field, or the equivalent of the Earth's Van Allen Belts. The FPGA's have SEU detection and use scrubbing for error correction. The Rovers have solar panels generating around 140 watts.

The Spirit unit became stuck in 2009, and engineers were unable to free it after 9 months of trying. It was re-tasked as a stationary sensor platform. Contact was lost in 2010. The Opportunity Rover lasted until February of 2019, after some 15 years of service

This mission was originally planned for 90 days, but the *Opportunity* Rover was still collecting useful data regarding potential life on our sister planet some 11 years later. It has traveled over 35 kilometers on the Martian surface. Ground based test units are used at JPL for evaluating problems seen on Mars, and for evaluating software and procedural fixes. Opportunity ceased operation in February 2019, having a fruitful mission of some 15 years.

In June of 2018, a massive Martian dust storm covered Curiosity, most importantly its solar panel, with a large amount of duct. The last communications was on June 10.

Mars Reconnaissance Orbiter

This mission launched in 2005, and remains operational at this writing. It was only scheduled to operate until 2008. By 2010, it had already transmitted more than 100 terabits of data to Earth. It joined five other active spacecraft at Mars. It serves as a telecommunications relay, and a weather mapper. It is searching for ideal landing sites for future crewd missions. It is modelled after the Mars Global surveyor.

MRO has two highly efficient solar panels for power, each panel

generating a thousand watts. There are dual 50 ampre-hour batteries. The main computer is a rad-hard Rad-750, a special version of a PowerPC 750.

MRO has determined that Mars' north polar ice cap holds a total of 30% of the capacity of the current Greenland Ice Cap. MRO has also imaged the Phoenix lander on the surface, and the tracks of the Opportunity rover. MRO has confirmed the existance of flowing salty water on Mars.

Phoenix Lander

This was launched in 2007, and landed on Mars in 2008. Its mission ended in November of that year. It's mission was to search for microbial life, and to look for water. It completed its mission in August of 2008. After the Martian winter, the craft could not be contacted. It had a 90 day projected life on the surface, but exceeded this by 2 months. It uses solar panels for power. It can relay data to Earth via the orbiting Mars Odyssey, MRO, and ESA's Mars Express.

Its landing was observed by these three spacecraft as well. The lander is a stationary platform, not a rover, and has a robotic arm and onboard analyzers. It dug a bit, and was able to confirm the existence of water ice just under the surface.

It had a three month defined mission, and exceeded this by 2 months. It succumbed to a dust storm, that covered its solar panels. Before this, it found snow falling from clouds.

Dawn

The Dawn Mission launched in 2007, and completed a Mars fly-by in 2009. It then continued onto to asteroids Vesta and Ceres. It is currently orbiting Ceres.

It used Mars for a gravity assist flyby. This stolen energy is estimated to have cost Mars a loss in velocity of 2.5 cm over 180 million years. Tough it out, Mars. The Dawn mission is still

operating at this writing.

Mars Helicopter Scout

The next mission in 2021 will include the 2020 Rover, which has a robotic helicopter. It will be an eye-in-the-sky, looking out for hazards, planning a path, and see things that the rover's camera can't. It will be autonomous in operation. It is a technology demonstration, planned to fly five times, during the early mission. The copter blades are a meter in diameter, and it has two counter-rotating sets. Compasses can't work on Mars due o the low magnetic field, so it will use solar tracking abd inertial guidance. It will have its own solar panels. It is carried under the rover. It is dropped to the ground, and the rover moves some distance away so it can ascend. It run linux.

Mars Science Laboratory Curiosity

The Mars Science Laboratory (MSL) landed successfully on the Martian surface on August 6, 2012. It had been launched on November 26, 2011. It's location on Mars is the Gale crater, and was a project of NASA's Jet Propulsion Laboratory. The project cost was around $2.5 billion. It is designed to operate for two Martian years (sols). The mission is primarily to determine if Mars could have supported life in the past, which is linked to the presence of liquid water. NASA has a Planetary Protection Officer assigned to Mars, to make sure we don't contaminate it with Earth life, and to protect any lifeforms that we may find there. So far, Earth is the only place we are aware of that has life. Is life on Earth unique in the Universe, or it is common? Mars may hold that answer for us.

Gale Crater is a location of interest. It's about 96 miles in diameter, and has a mountain, Aeolis Mons, in the center that is 18,000 feet high.

The Rover vehicle *Curiosity* weights just about 1 ton (2,000 lbs.)

and is 10 feet long. It has autonomous navigation over the surface, and is expected to cover about 12 miles over the life of the mission. The platform uses six wheels The Rover Compute Elements are based on the BAE Systems' RAD-750 CPU, rated at 400 mips. Each computer has 256 Mbytes of RAM, and 2 Gbytes of flash memory. The power source for the rover is a radioisotope thermal power system providing both electricity and heat. It is rated at 125 electrical watts, and 2,000 thermal watts, at the beginning of the mission. The operating system is WindRiver's VxWorks real-time operating system. The vehicle was assembled and tested at NASA's Goddard Space Flight Center, and shipped to lead center JPL. The landing location in Gale Crater was named Bradbury Landing, after the science fiction writer, Ray Bradbury. Mars figured heavily in his writings. Gale Crater is named after an Australian amateur astronomer, Walter Gale. There is some evidence that the crater was once filled with water.

The computers interface with an inertial measurement unit (IMU) to provide navigation updates. The computers also monitor and control the system temperature. All of the instrument control, camera systems, and driving operations are under control of the onboard computers.

Communication with Earth uses a direct X-band link, and a UHF link to a relay spacecraft in Mars orbit. At landing, the one-way communications time to Earth was 13 minutes, 46 seconds. This varies considerably, with the relative positions of Earth and Mars in their orbits around the Sun.

The science payload includes a series of cameras, including one on a robotic arm, a laser-induced laser spectroscopy instrument, an X-ray spectrometer, and x-ray diffraction/fluorescence instrument, a mass spectrometer, a gas chromotograph, and a laser spectrometer. In addition, the rover hosts a weather station, and radiation detectors. There is cooperation between in-space assets and ground rovers in sighting dust storms by the meteorological satellite in Mars orbit.

In 2013, NASA uploaded a software upgrade to Curiosity's operating System. Overall, it took a week to install.

Curiosity's exploration of the ancient lake bed, known as Gale Crater resulted in some new discoveries that NASA released on June 7, 2018. It found organic molecules, particularly methane, below the surface. Curiosity has a sampling drill (that, unfortunately, is limited to 5 cm.), a mass spectrometer, and a gas chromatograph. On Earth, most methane is from biological processes. It can be produced by in-organic processes, however. Scientists have also discovered a seasonal pattern in the amount of methane in the atmosphere, in the amount of a factor of three, that may point to sub-surface storage. Methane was first detected on Mars in 2003.

The source of the Mars methane has to be resolved. This will be a major goal of NASA's and ESA's next landers. A large underground reservoir of methane could be very useful for return-trip rocket fuel.

Maven

NASA's Maven mission to Mars is an orbiter. It is studying the Martian atmosphere It was launched in November of 2013, and reached Mars in September of 2014. Maven is an acronym for Mars Atmosphere and Volatile Evolution Mission.

MAVEN is equipped with a RAD-750 Central Processing Unit manufactured by BAE Systems in Manassas, Va. The processor can endure radiation doses that are a million times more extreme than what is considered fatal to humans. The RAD750 CPU itself can tolerate 200,000 to 1,000,000 rads. Also, RAD750 will not suffer more than one event requiring interventions from Earth over a 15-year period.

The RAD750 operates at temperatures of -55°C to 125°C with a power consumption of 10 Watts.

One discovery by Maven is that Mars' atmosphere deteriorates during solar storms. Maven can also serve as a communications relay for rovers on the surface. It is currently operational.

Insight

The Insight Mission launched in May of 2018, and is scheduled to land on Mars in November of that year. It is a robotic lander with a seismometer and a heat transfer probe. It is based on the Phoenix design.

The mission will land near the Martian equator, which will provide maximum solar power during the 2-year mission. It is on its way to Mars, as this book is being prepared.

The hope is, we can establish a refueling station on Mars or one of its moons, so we don't need to carry our return fuel with us. Since Mars has been proven to have water ice, this might be quite feasible. Using solar energy, you can break down water into liquid hydrogen and liquid oxygen – rocket fuel and oxydizer. NASA has published a map of water ice on Mars, and ESA's Mars Express spacecraft spotted the remails of an ancient river system and lake.

Interplanetary Cubesats

Mars Cube One (MarCO) is the first interplanetary cubesat mission, headed by JPL. It involves sending two Cubesats to Mars, along with the Insight Rover. The 6U cubesats will separate at Earth orbit and proceed on their own. The mission was to be launched in March, 2016, when Mars was 1.07 AU distant, and arrive in September of 2016. The launch was postponed, however, due to a vacuum leak in the prime instrument. The mission was rescheduled for Spring, 2018, and they are on their way, as of this writing.

A Cubesat is a small, affordable satellite that can be developed and

launched by college, high schools, and even individuals. The specifications were developed by Academia in 1999. The basic structure is a 10 centimeter cube, (volume of 1 liter) weighing less than 1.33 kilograms. This allows multiples of these standardized packages to be launched as secondary payloads on other missions. A Cubesat dispenser has been developed, the Poly-PicoSat Orbital Deployer, P-POD, that holds multiple Cubesats and dispenses them on orbit. They can also be launched from the Space Station, via a custom airlock. ESA, the United States, and Russia provide launch services. The Cubesat origin lies with Prof. Twiggs of Stanford University and was proposed as a vehicle to support hands-on university-level space education and opportunities for low-cost space access. This was at a presentation at the University Space Systems Symposium in Hawaii in November of 1999.

The Cubesats will serve as a real-time communications relay with Earth during the critical descent and landing phase of the rover. The lander talks to the Cubesat relays over an 8kbps UHF link, and the Cubesats relay this to Earth over an 8kbps X-band link to the DSN.

The Cubesats are stabilized with reaction wheels, and have propulsion systems to unload the wheels, and adjust their orbital position.

The Russian/Soviet Mars Missions

Russian tried five Mars missions from 1960-1962. There were four launch failures, and the other lost communication before it reached the red planet. The same thing happened to another try in 1964. Three more launch failures came in 1969-1971. Finally, the Mars 2 and Mars 3 spacecraft reached and orbited in May of 1971, and operated for 362 orbits. These spacecraft deployed landers to the Martian surface. The small rovers were equipped with skis, and tethered to the lander with a umbilical of 15 meters. The Mars 2 became the first spacecraft to impact the Martian surface. It's location is unknown.

Over twenty Russian/Soviet Mars spacecraft have been the victims of launch or payload failure.

Phobos-Grunt

In November of 2010, the Russian Space Agency launched an ambitious mission to set a probe down on the small Martian moon Phobos, collect samples, and return them to Earth.

There was a failure of the spacecraft propulsion system that stranded the mission in Earth orbit. It re-entered the Earth's atmosphere in January 2011.

Various causes were postulated for the failure, including interference by U.S. Radar, cosmic ray induced upsets, programming errors, and counterfeit chips.

The final report from Roscosmos cited software errors, failure of chips in the electronics, possibly due to radiation damage, and the use of non-flight qualified electronics, with inadequate ground testing.

Evidently, identical chips in two assemblies failed nearly simultaneously, so quickly that an error message was not generated. It was possible that the error was recoverable, as the spacecraft entered a safe mode with a proper sun orientation for maximum power. However, the design precluded the reset mode before the spacecraft left its parking orbit. This was major design oversight.

The identified chips that failed were 512k SRAM. The part numbers from the Russian report were checked by NASA's Jet Propulsion Lab, and were found to be among the most radiation susceptible chips they had ever seen. Bad choice. The chips could last in space a few days, and were barely acceptable for non-critical applications, The probably failure cause was single event latch-up, which is sometimes recoverable. In single event latch up,

there is a single particle strike that latches up a transistor, preventing it from operating. Usually, if you turn it off and back on again, it will work. A lot of radiation damage to the underlying semiconductor lattice fixes itself after a while, a process called "annealing." Common practice is to use radiation-harden parts.

ESA Missions

This section discusses the Mars missions of the European space agency. ESA has 22 member states, that participate and cooperate in missions and launches. It was founded in 1975. It operates a launch site in French Guiana on the east coast of South America. There is an ongoing study mission for human visitation, called Aurora.

Mars Express

This mission, in 2003, was a success, and remains so as of this writing. A lander, Beagle2, was deployed, but its solar panels failed to deploy, ending its part of the mission. The orbiter uses solar panels for power. Due to adoption of standards for interplanetary communication, the spacecraft is inter-operable with NASA's Deep Space Net.

Rosetta

This mission was launched in 2004, and conducted a successful imaging flyby of Mars in 2007, en-route to its primary target, a comet.

The Indian Mars Mission

The Mangalyaan orbiter was launched in 2013, and entered Mars orbit in September of 2014. It is operational at this writing, and has an extended mission through 2020. India is the first nation to reach Mars successfully on its first attempt. The spacecraft spent about a month in Earth orbit, before beginning a trans-Mars injection maneuver. It is operated from the ISRO Control Center in

Bangalore. It was lifted to orbit by the Indian (Polar Satellite Launch Vehicle) PSLV-XL launch vehicle. The spacecraft has three solar array panels, providing 840 watts of power at Mars.

The mission was planned for a 6-month duration, but is heading into its fourth year. The spacecraft weighs 1336 kg, and is a 1.5 meter cube. The mission has already exceeded expectations, came in under budget, and is returning significant new data about Mars.

A second mission is planned for the launch opportunity in 2020.

United Arab Emirates

The UAE Mars Al-Amal (Hope) mission is being implemented now and is scheduled for launch in 2020 as of this writing. It's mission is to study the Martian atmosphere, and, most importantly, bring a new player into the field. The Mission was announced in 2014, and is being implemented by the UAE Space Agency, and the Mohamed bin Rashid Space Center.

The launch mass is targeted at 1,500 kg. It will orbit the planet between 22,000 and 44,000 km. The selected launch vehicle is Japanese, from Mitsubishi Heavy Industries, the H-IIA. The instrument suite will include an imager, an Infrared spectrometer, and an Ultraviolet spectrometer.

Chinese Mars Mission

The Yinghuo-1 was deployed with the ill-fated Phobos-Grunt mission in 2011, and did not make it past Earth parking orbit. End of mission occurred in January of 2012, when it reentered the atmosphere, and burned. The Mission was a outgrowth of a Cooperative Agreement between the Russian and Chinese Space Agency's. Another potential Chinese Mars mission is scheduled for the 2020 launch opportunity.

Future Missions

The most exciting mission will be the crewed mission to Mars. In the meantime, there are more robotic exploration missions planned for the next launch opportunity in 2020. In addition to the Emirates Mars Mission and the Chinese Mars Mission, ESA is planning the ExoMars mission in partnership with Roscosmos. The U. S. is planning a Mars-2020 mission that will include a helicopter. Japan would like to send a microsatellite in the 2020 opportunity window, as well as a Martian Moons Exploration mission. Indian is planning their second Mars mission also

Exo-MARS

Exo_Mars is an astrobiology mission to search for evidence of present or past life on Mars. The first part was launched in 2016. This was a communications satellite in Mars orbit that can also do research on trace gases. The mission carried the Schiaparelli lander, which, unfortunately, crashed. The second part of the mission will put a lander and rover on the surface for exploration. It will look at water and trace gases, and also bio-signatures of possible Martian life. This lander, built by Roscosmos, will deploy the rover. The lander will do a controlled descent with parachutes and retro-rockets. The exobiology laboratory, named Pasteur, will look for signs of life.

Mars-2020

This U. S. Program is a surface rover mission. It is designed to study astro-biology, surface geological processes and assess past habitability of the planet. It will search for bio-signatures in geological materials.

The Rover will be a 6-wheeled derivative of the Curiosity design. It is a JPL mission. It is being discussed how the Rover could launch collected samples to Mars orbit, and how these could then be returned to Earth. The rover will be accompanied by a drone helicopter, to scout out in front for potential areas of interest, and

hazards.

The Hope Mars Mission

I want to mention this mission here, although it does not involve a lander. The Hope mission is being developed by The Emirates, not a big player in the space exploration business, just yet. This is slated to reach Mars in 2021. It will study atmosphere and climate. It will also put the Emirates in the fraternity of spacefaring nations. Welcome to Mars.

Getting to Mars

Getting to Mars is not easy, and requires a lot of energy and time. First, we get to Earth orbit, and check that all the systems have survived launch. Knowing where Mars is currently, we can calculate the correct point to head to, when our mission reaches the correct distance. When the mission reaches Mars, we have to slow down and enter Martian orbit. Counter-intuitively, a minimum energy mission (but not a minimum time scenario) takes us looping past Venus to get to Mars in an efficient manner.

The distance from Earth to Mars varies on their relative positions in their orbits, but ranges from 33.9 to 250 million miles.

Every 26 months, the Earth and Mars align such that a minimum energy transfer can get a spacecraft from one to the other. The implications are that if you miss the launch window, you need to wait some 2 years, and that there is a minimum time for a Earth to Mars journey, landing, and return to Earth. This sets a mission duration that is important for future crewed missions. The travel time for this path is about nine months.

A Hohmann transfer orbit is an elliptical orbit between the circular orbits of two planets. It allows for the maximum payload to be sent with a given energy expenditure (or, amount of rocket fuel). You can get there quicker expending more energy. The alignment, or launch window, is critical. The details of the interplanetary transfer orbit were defined and published by German scientist Walter

Hohmann in 1925.

The hope is, we can establish a refueling station on Mars or one of its moons, so we don't need to carry our return fuel with us. Since Mars has been proven to have water ice, this might be quite feasible. Using solar energy, you can break down water into liquid hydrogen and liquid oxygen – rocket fuel and oxidizer.

Interplanetary Internet

Communications between planets in our solar system involves long distances, and significant delay. New protocols are needed to address the long delay times, and error sources.

A concept called the Interplanetary Internet uses a store-and-forward node in orbit around a planet that burst-transmits data back to Earth during available communications windows. At certain times, when the geometry is right, the Mars bound traffic might encounter significant interference. Mars surface craft communicate to Orbiters, which relay the transmissions to Earth. This allows for a lower wattage transmitter on the surface vehicle. Mars does not (yet) have the full infrastructure that is currently in place around the Earth – a network of navigation, weather, and communications satellites.

For satellites in near Earth orbit, protocols based on the cellular terrestrial network can be used, because the delays are small. In fact, the International Space Station is a node on the Internet. By the time you get to the moon, it takes about a second and a quarter for electromagnetic energy to traverse the distance. Delay tolerant protocols were developed for mobile terrestrial communication, but don't work in very long delay situations.

We have a good communications model and a lot of experience in Internet communications. One of the first implementations for space used a File Transfer Protocol (FPP) running over the CCSDS space communications protocol in 1996.

The formalized Interplanetary Internet evolved from a study at JPL, lead by Internet pioneer Vint Cerf, and Adrian Hook, from the

CCSDS group. The concepts evolved to address very long delay and variable delay in communications links.

The Interplanetary Internet implements a Bundle Protocol to address large and variable delays. Normal IP traffic assumes a seamless, end-to-end, available data path, without worrying about the physical mechanism. The Bundle protocol addresses the cases of high probability of errors, and disconnections. This protocol was tested in communication with an Earth orbiting satellite in 2008.

Crewed Missions

Space-X wants to launch space tourists to Mars by the 2020's. NASA is targeting getting astronauts near or on the surface of Mars by 2030.

Orion Capsule

The initial missions of Orion will be flights to the International Space Station for crew substitution and resupply of consumables. The Orion capsule is reusable, and supports a crew of four. A first, un-crewed launch was successful in 2014 by a Delta-IV Heavy vehicle out of Launch Complex 37 at Cape Canaveral. The capsule was recovered at sea. The Orion is anticipated to be the basis for a series of lunar, and later, Mars missions. The pressurized volume is 691 cubic feet, with a habitable volume of 316 cubic feet. The capsule has 50% more volume than Apollo.

Deep Space Gateway

The Deep Space Gateway (DSG) is a NASA Project for a crewed station in cis-lunar space. It is intended as a jumping-off point. The Orion crewed vehicle is scheduled to be used for this effort. The Gateway would be located in a halo orbit around the Moon. By that, we mean that the spacecraft would be visible to Earth for its entire orbital path. The DSG would form an in-orbit ecosystem to support missions to the lunar surface, and to Mars.

The DSG will result in a one-year crewed mission near the moon, to validate the concept of a flight to Mars. It is not so much the distance to Mars, as the relative orbital positions of the two planets in their solar orbits. The mechanics of the transfer orbit were worked out in 1925 by German scientist Walter Hohmann. In his 1928 book, *A Daring Trip to Mars,* Max Valier shows that one of the most efficient methods of reaching Mars from Earth involves a non-intuitive Venus fly-by. People have been thinking about this for a while. The shortest travel time occurs about every 26 years.

Using a standard Hohmann transfer orbit would involve a 9 month travel time, 500 days at Mars, and another 9 month return journey. Due to this time-frame, there is a significant radiation risk, both in space, and on the Martian surface. There is also the issue of lack of gravity for that period of time. Not only that, you could run out of potatoes.

Mars Analog Bases on Earth

Several Mars analog bases have been constructed, and long term studies have been conducted for year. One of these is in the Canadian Arctic, and another in Utah, in the American west. The analog bases allow teams to operate as if they were on Mars. They were spacesuits while outside, and communicate over delayed radio with “mission control.” Some missions have lasted a year or more.

A specific program addressing the Mars issues is the Flashline Mars Arctic Research Station (FMARS). There is currently one such facility in the Arctic, with a second planned. The existing station is on Devon Island in the Arctic sea. It is located on a ridge, overlooking a large impact crater, about a thousand miles from the North Pole. The facility was built in 2000, and is operated by the Mars Society, a non-profit. It is used to define and refine field procedures, test habitat design, study crew performance, and selection criteria. It began operations in 2001. Generally, there is a core crew of ten, with visiting researchers and assistants. A hazard probably not found on Mars is the occasional polar bear, looking

for a quick meal. One outside crew member is always armed. Communication to and from the station to external sources is delayed 20 minutes, to simulate the one-way radio/light travel time to Mars. The crew keeps to the somewhat longer Martian Sol day

The Biosphere -2 project, located in the Arizona desert, supports 8 humans for a year in a closed ecosystem.

The Chinese have a Mars Analog Base on the high planes of Tibet.

Mars Base Camp

When we send the first human mission to Mars, it would be nice if they could refuel there for the return trip. There is water ice below the surface. It is also possible that Mars' tiny moons contain water ice. Why water ice? You use solar power to break it down into hydrogen and oxygen – the perfect rocket fuel. A big advantage is that you don't need to carry the return mission fuel on the outgoing flight.

Human missions to Mars have gotten consideration for more than 150 years. Von Braun made a very detailed study of a Mars mission in 1952. Willy Ley had published a variation in 1949. By 1956, their modified mission design would required over 400 launches, assembly in space, but would provide a winged lander for Mars. The thought is to land there, and, now that we know the surface features, begin to terra-form the planet for our needs. Mars missions are in active planning by the United States, Russia, Europe, China, and several commercial entities. Since Mars and the Earth have different orbital periods (“years”) around the Sun, there are optimal times to make the journey. After working through all the math, the time between optimal Earth-Mars trips is 26 months. This provides the optimal energy expenditure. Using a Hohmann transfer, there would be a 9-month travel time, Earth to Mars, a 500 day stay at Mars to allow alignment of the orbits again, and another 9 month journey back. Can't we do better? Yes, but at the cost of fuel. There is a maneuver that would provide a

Venus and a Mars flyby in one mission, with no landings. All of these long duration missions offer various hazards, and will be operating in “unknown territory” in terms of a group of humans isolated in a small space for a long time.

A NASA study by three major aerospace companies in 1962, showed a Mars mission requiring 8 Saturn-V “moon rockets,” with assembly in Earth orbit. Von Braun's Mars Mission was passed over in favor of the Space Shuttle Project. Mars has been studied by fly-by, orbiting, and lander missions since 1981. NASA's Mars Design Reference Mission of the 1990's assumed that fuel could be synthesized from Martial atmospheric or surface components. The design studies continue to this day.

The Mars Base Camp is a crewed Mars orbiter, proposed by Lockheed Martin, possibly ready for the 2028 favorable launch opportunity. The hardware would use the Orion MPCV. Although the humans would remain in Mars orbit, they would perform tele-operation experiments on the surface. The mission would be launched from lunar orbit. The first mission is named Mars Base Camp-1. A crew of 6 would spend a year in Martian orbit. Interplanetary missions generally provide very limited options for abort/early return scenarios.

Lockheed defined a road map of the technologies required to achieve the Mission. The parts include: the Multi Purpose Crew Vehicle (MPCV), which is the orbital command and control center, implementing navigation, communications, life support and habitat systems. The Solar Array subsystem provides power for the system, including the electric propulsion engines. This is being developed by the NASA-Glenn Center. Radiators control dumping of excess heat. The propulsion stage uses cyrogenic fuels. Side visits to the moons Phobos and Deimos are planned. The main part of the assembly will consist of an Orion capsule with an associated service module, and an excursion module. There will be a laboratory and workshops. The excursion modules will provide access to the Martian (and Mars lunar surfaces.)

The Mars hardware and operations would be checked out at the Deep Space Gateway. The eventual goal is to establish a self-sustaining colony, and perhaps terra-form the Red Planet to be friendlier to Earth life, plant and animal.

The MPCV would provide housing, life support, transportation, and command & control. Large solar arrays would be used, as the vehicle is designed for electric propulsion. In addition, an onboard 3-D printer is seen as an alternative to manifesting spares.

A follow-on concept is a winged Mars surface lander, using liquid hydrogen and liquid oxygen engines. The fuel and oxidizer would be derived from water, electrolized using solar energy. Initially, the water would be shipped from Earth or the Moon, with a goal of processing water on the Martian surface, or its moons. NASA sees an opportunity for commercial firms to supply the water. A Water Delivery Vehicle (WDV) with a capacity of over 50 metric tons would be required. This will dock with a 375 kilowatt electrolysis plant in orbit. The Earth-rated 375 kw plant degrades to 160kW (42.6%) at Mars' greater distance from the Sun.

Modules would be delivered and pre-positioned in Mars orbit, including a lander (The Mars Ascent/Descent Vehicle) and a cyrogenic fuel depot. The MADV touches down and launches vertically. It will house 4 crew for a 10-day duration on the surface. The MADV's engines will use liquid hydrogen and oxygen for an efficient Isp of 405 seconds. Six RL-10 class engines are postulated.

The lander will have crew accommodations for four, on three decks. There is to be a flight deck, crew quarters on the mid deck, and an aft deck with galley, lab facilities, and the airlock.

Solar electric propulsion using xenon gas will be feasible with large solar arrays. The Deep Space Gateway will use this approach for station-keeping.

One timeline shows a cis-lunar outpost starting in 2021, with lunar surface science by 2024. There could be a pre-deployment of assets to Mars by 2026. The year 2028 is targeted for the Mars mission.

Besides the government mission, certain private spacecraft companies are defining their own Mars missions.

Commercial ventures such as Elon Musk's SpaceX are also interested in a Mars Colony. Musk, the founder of PayPal, put his own money into the company. It has developed its own launch vehicle, the Falcon, and has a 12-trip resupply contract for the ISS. SpaceX's approach to the uncrewed resupply missions is unique. The capsule is recovered and reused, saving a lot of money.

There are two 3D printers on the ISS, made by a California Company, Made-in-Space. NASA is exploring having the capability of printed custom parts in situ, as opposed to carrying spares, as a key for the Mars mission. Made-in-Space sees the orbital facility as an ideal location to manufacture optical fiber. Currently, items are printed for use onboard the station, as opposed to sending them up on a resupply flight, and other items are printed and returned to Earth for testing. A practical device that was printed was a buckle for exercise equipment, designed by Astronaut Yvonne Cagle.

Mars Crewed Fly-by

In 2013, the Inspiration Mars Foundation, a non-profit founded by Entrepreneur Dennis Tito, proposed a manned mission for a MARS fly-by for 2018. The details have been removed from the Website. This was estimated to require up to $2 billion ($10^9$) dollars. Space-X had been contacted as a possible vehicle provider. A “Plan-B” was defined using the known Venus-Mars flyby, for 2021 (when the planets were aligned properly).

There is also a one-way trip option proposed by several space enthusiasts. This option assumes you get it right the first time, and there are still a lot of unknowns. On the other hand, establishing a colony may be easier than the return journey. The current thinking is to launch the habitats and required equipment before the crew. It is still a leap of faith.

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Glossary of terms and definitions

Areography – equivalent of geography on Earth.
Apogee – furthest point in the orbit from the Earth.
Apoareion – farthest point in orbit, from Mars.
ASIN – Amazon Standard Inventory Number
Astrionics – electronics for space flight.

AU – astronomical unit.
Baud – measure of data rate; bits per second
BEM – bug-eyed monster
BEO – beyond Earth orbit.
Byte – data structure of 8 bits.
CBM – common berthing mechanism.
CCS – command computer system
CCSDS – Consultive Committee on Space Data Systems, a standards organization.
CM – crew module
CME – Coronal Mass Ejection, blast of energetic particles from the Sun.
CMP – co-manifested payload.
CNSA – China National Space Administration.
Conops – concept of operations.
CPS – Cyrogenic Propulsion Stage.
CPU – central processing unit
CRTBP – Circular Restricted three-body Problem.
CSA – Canadian Space Agency, Agence Spatiale Canadienne
CSF – Cislunar Support Flight.
C&W – caution and warning.
Cygnus – Orbital-ATK automated cargo vehicle for ISS.
Cyrogenic – relating to very low temperatures.
DAM – damage avoidance maneuver.
DCM – docking cargo module.
Delta-V – change in velocity.
DoD – (U.S.) Department of Defense
DRG – Distant Retrograde Orbit.
DRM – design reference mission.
DSG – Deep Space Gateway
DSH – deep space habitat.
DSN – (NASA) Deep Space Network.
DST – Deep Space Transport
DTM – dynamic test model, for structural tests.
ECLSS – Environmental Control & Life Support system.
EDL – Entry, Descent, Landing.
EM-x Exploration Mission number-x.

EMM – Emirates Mars Mission.
Ephemeris – position information data set for orbiting bodies, 6 parameters plus time.
Epoch – a reference point in time for orbital elements.
EPS – electrical power system
ESA – European Space Agency
EUS – Exploration Upper Stage.
EVA – extra-vehicular activity.
Flash – a type of non-volatile memory
FMARS – Flashline Mars Arctic Research Station
FPGA – Field Programmable Gate Array – an integrated circuit
FTL – faster than light
FTP – file transfer protocol.
G – one Earth normal gravity; as a prefix, 10^{12}
GCSC – Guidance, control, sequencing.
GHZ - giga-Hertz
GNC – Guidance, Navigation, and Control.
Gravity well – a conceptual model of the gravity field near a mass.
GSFC – NASA Goddard Space Flight Center, Greenbelt, MD.
GYRO – sensor for orientation.
Halo Orbit – three dimension orbit near the L1, L2, or L3 Lagrange points.
HEEO – highly eccentric Earth orbit.
Hemitite – an iron ore Fe_2O_3. It's red.
HEOMD – Human Exploration and Operations Mission Directorate.
HITL – Human in the loop.
HOPE – Human Outer Planet Exploration (NASA)
HSIR – human systems integration requirements
IDSS – International Docking System Standard.
IGA - (ISS) InterGovernmental Agreement
IMU – inertial measurement unit.
IP – internet protocol
ISP – specific impulse. Measure of efficiency of rocket engine. Units of seconds.
ISRO – Indian Space Research Organization
ISRU – in situ resource utilization

ISS – International Space Station
JAXA – Japan Aerospace Exploration Agency.
KW – kilowatt.
IDSN – Indian deep space network
ISRU – in site resource utilization.
ISS – International Space Station
JAXA – Japanese space agency
JPL – Jet Propulsion Laboratory, Pasadena, CA.
JSC – Johnson Space Center, Houston, Texas.
K, kilo - 10^3
KSC – NASA Kennedy Space Center, launch site, Florida.
L2 – second of 5 Lagrange points, a null in the gravity field in the restricted 3-body problem.
LAS – launch abort system
Lbf – pounds, force.
LCT – Lunar Cargo Transportation.
LEO – Low Earth Orbit
LH2 – liquid hydrogen.
Libration point – null in the gravity field of the three body problem.
LOS – Russian Lunar Orbital Station; loss-of-signal.
LOX – liquid oxygen, boils at -297 F.
LSAM – lunar surface access module
LSPPO – Lunar Surface systems Project Office (NASA-JSC).
LST – landing by soft touchdown.
MADV – Mars Ascent/Descent Vehicle.
MBC – Mars Base Camp.
MER – Mars Exploration rover
MET – mission elapsed time.
MHS – Mars Helicopter Scout.
MHz – mega (10^6) hertz
MIPS – millions of instructions per second.
MMSEV – MultiMission Space Exploration Vehicle.
MOU – memorandum of understanding.
MPCV - Multi-Purpose Crew Vehicle.
MPH – miles per hour
MPLM – Multi-purpose Logistics Module.

MRO – Mars Reconnaissance Orbiter
m/s – meters per second.
MSL – Mars Science Laboratory
MT – metric ton, 1000 kg.
N – Newton, metric unit of force.
NAC – NASA Advisory Council.
Nadir – the point directly below.
NASA – (U.S.) National Aeronautics and Space Administration
NEO – near Earth object.
NextSTEP-2 – (NASA) Next Space Technologies of Exploration Partnerships.
NHV – net habitable volume.
NRHO – Near rectilinear halo orbit (around the L1 or L2 Earth-Moon libration point).
NTIS – National Technical Information Service (www.ntis.gov).
NTRS – NASA Technical Reports Server, ntrs.nasa.gov
ORU – Orbital Replacement Unit.
OPSEK – (Russian) Orbital Piloted Assembly and Experiment Complex.
OWLT – one-way light time.
RAD – unit of radiation
Perigee –closest point in the orbit from the Earth.
Periareion – closest point in orbit to Mars.
PMA – Pressurized mating adapter.
PMCU – Power Management Control Unit.
PPB – power and propulsion bus.
PPO – Planetary protection officer.
PSI – Planetary Science Institute, Arizona, US
PTCS – Passive thermal control system
PVCU – Photo Voltaic Control Unit.
R&D – research & development.
RAM – random acess memory
RCS – reaction control system.
Regolith – layer of loose material, covering rock; dirt.
RGA – rate gyro assembly
ROSCOSMOS – Russian Space Agency.
RPOD – Rendezvous, Proximity Operations, Docking.

RTG – Radioisotope Thermoelectric Generator.
SEP – solar electric propulsion.
SEU – single event upset, transient error in a digital circuit, usually due to radiation.
SHFE – space human factors engineering.
SI – System International – the metric system.
Sidereal period – time for an object to make a full orbit.
Sol, local solar day – on Mars, 24h, 37 min.
SLS – (NASA) Space Launch System.
SPACE Act - Spurring Private Aerospace Competitiveness and Entrepreneurship
SPACE-X – private space company
Synodic period - time for an object in orbit to occupy the same point, in relation to 2 other objects.
TCS – thermal control system.
Tera – 10^{12}
TLI – Trans-lunar injection.
TM – Technical Manual.
TPS – thermal protection system.
Trillion - 10^{12}
TRL – technology readiness level.
UAE – Unted Arab Emirates
UDM – universal docking module.
UHF – ultra high frequency, 300 MHz to 3 Ghz
Ullage – residual fuel or oxidizer in a tank after engine burn is complete.
USAF – United States Air Force.
USGS - United States Geologic Survey
V&V – verification and validation.
WDV – water delivery vehicle.
X-band – 8 – 12 GHz.
XBASE - Expandable Bigelow Advanced Station Enhancement.
Zenith – the point directly above.
Zombie-sat – a non functional satellite in orbit, contributing to the orbital debris problem.

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